Neutrino Mass from Laboratory: Contribution of Double Beta Decay to the Neutrino Mass Matrix

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Double beta decay is indispensable to solve the question of the neutrino mass matrix together with ν oscillation experiments. The most sensitive experiment - since eight years the HEIDELBERG-MOSCOW experiment in Gran-Sasso - already now, with the experimental limit of $\langle m_\nu \rangle < 0.26$ eV practically excludes degenerate ν mass scenarios allowing neutrinos as hot dark matter in the universe for the smallangle MSW solution of the solar neutrino problem. It probes cosmological models including hot dark matter already now on the level of future satellite experiments MAP and PLANCK. It further probes many topics of beyond SM physics at the TeV scale. Future experiments should give access to the multi-TeV range and complement on many ways the search for new physics at future colliders like LHC and NLC. For neutrino physics some of them (GENIUS) will allow to test almost *all* neutrino mass scenarios allowed by the present neutrino oscillation experiments.

1. Introduction

Recently atmospheric and solar neutrino oscillation experiments have shown that neutrinos are massive. This is the first indication of beyond standard model physics. The absolute neutrino mass scale is, however, still unknown, and only neutrino oscillations and neutrinoless double beta decay *together* can solve this problem (see, e.g. [1–3]).

In this paper we will discuss the contribution, that can be given by present and future $0\nu\beta\beta$ experiments to this important question of particle physics. We shall, in section 2, discuss the expectations for the observable of neutrinoless double beta decay, the effective neutrino mass $\langle m_\nu \rangle$, from the most recent ν oscillation experiments, which gives us the required sensitivity for future $0\nu\beta\beta$ experiments. In section 3 we shall discuss the present status and future potential of $0\nu\beta\beta$ experiments. It will be shown, that if by exploiting the potential of $0\nu\beta\beta$ decay to its ultimate experimental limit, it will be possible to test practically *all* neutrino mass scenarios allowed by the present neutrino oscillation experiments (except for one, the hierarchical LOW solution).

2. Allowed ranges of $\langle m \rangle$ by ν oscillation experiments

After the recent results from Superkamiokande (e.g. see [16]), the prospects for a positive signal in $0\nu\beta\beta$ decay have become more promising. The observable of double beta decay $\langle m \rangle = |\sum U_{ei}^2 m_i| = |m_{ee}^{(1)}| + e^{i\phi_2}|m_{ee}^{(2)}| + e^{i\phi_3}|m_{ee}^{(3)}|$ with U_{ei} denoting elements of the neutrino mixing matrix, m_i neutrino mass eigenstates, and ϕ_i relative Majorana CP phases, can be written in terms of oscillation parameters [1,2]

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1, \tag{1}$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2}, \tag{2}$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2}. \tag{3}$$

The effective mass $\langle m \rangle$ is related with the half-life for $0\nu\beta\beta$ decay via $(T_{1/2}^{0\nu})^{-1} \sim \langle m_\nu \rangle^2$, and for the limit on $T_{1/2}^{0\nu}$ deducable in an experiment we have $T_{1/2}^{0\nu} \sim a\sqrt{\frac{Mt}{\Delta E B}}$. Here are a - isotopical abundance of the $\beta\beta$ emitter; M - active detector mass; t - measuring time; ΔE - energy resolu-

tion; B - background count rate. Neutrino oscillation experiments fix or restrict some of the parameters in eqs. 1-3, e.g. in the case of normal hierarchy solar neutrino experiments yield Δm^2_{21}, $|U_{e1}|^2 = \cos^2\theta_\odot$ and $|U_{e2}|^2 = \sin^2\theta_\odot$. Atmospheric neutrinos fix Δm^2_{32} and experiments like CHOOZ, looking for ν_e disapperance restrict $|U_{e3}|^2$. The phases ϕ_i and the mass of the lighest neutrino, m_1 are free parameters. The expectations for $\langle m\rangle$ from oscillation experiments in different neutrino mass scenarios have been carefully analyzed in [1,2].

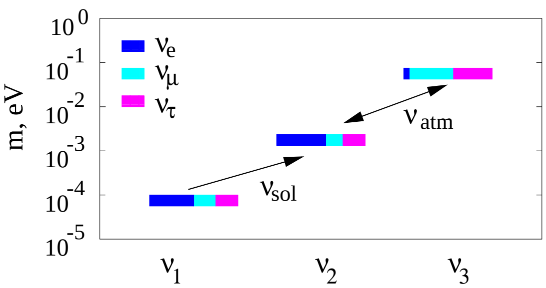

Figure 1. Neutrino masses and mixings in the scheme with mass hierarchy. Coloured bars correspond to flavor admixtures in the mass eigenstates ν_1, ν_2, ν_3. The quantity $\langle m\rangle$ is determined by the dark blue bars denoting the admixture of the electron neutrino U_{ei}.

2.1. Hierarchical spectrum ($m_1 \ll m_2 \ll m_3$)

In hierarchical spectra (Fig. 1), motivated by analogies with the quark sector and the simplest see-saw models, the main contribution comes from m_2 or m_3. For the large mixing angle (LMA) MSW solution which is favored at present for the solar neutrino problem (see [15]), the contribution of m_2 becomes dominant in the expression for $\langle m\rangle$, and

$$\langle m\rangle \simeq m^{(2)}_{ee} = \frac{\tan^2\theta}{1+\tan^2\theta}\sqrt{\Delta m^2_\odot}. \tag{4}$$

In the region allowed at 90% c.l. by Superkamiokande according to [16] the prediction for $\langle m\rangle$ becomes

$$\langle m\rangle = (1-3)\cdot 10^{-3}\ \text{eV}. \tag{5}$$

The prediction extends to $\langle m\rangle = 10^{-2}$ eV in the 99% c.l. range (Fig. 2).

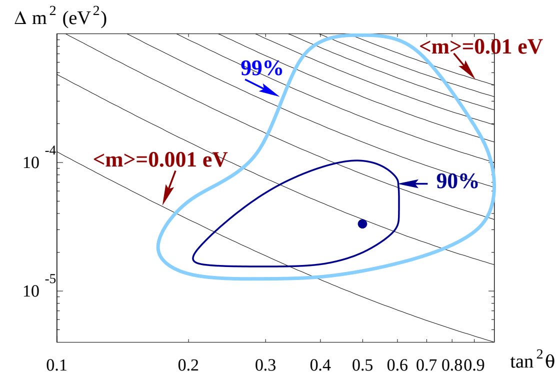

Figure 2. Double beta decay observable $\langle m\rangle$ and oscillation parameters in the case of the MSW large mixing solution of the solar neutrino deficit, where the dominant contribution to $\langle m\rangle$ comes from the second state. Shown are lines of constant $\langle m\rangle$, the lowest line corresponding to $\langle m_\nu\rangle$ = 0.001 eV, the upper line to 0.01 eV. The inner and outer closed line show the regions allowed by present solar neutrino experiments with 90 % C.L. and 99 % C.L., respectively. Double beta decay with sufficient sensitivity could check the LMA MSW solution. Complementary information could be obtained from the search for a day-night effect and spectral distortions in future solar neutrino experiments as well as a disappearance signal in KAMLAND.

2.2. Inverse Hierarchy ($m_3 \approx m_2 \gg m_1$)

In inverse hierarchy scenarios (Fig. 3) the heaviest state with mass m_3 is mainly the electron neutrino, its mass being determined by atmospheric neutrinos, $m_3 \simeq \sqrt{\Delta m^2_{atm}}$. For the LMA MSW solution one finds [2]

$$\langle m\rangle = (1-7)\cdot 10^{-2}\ \text{eV}. \tag{6}$$

2.3. Degenerate spectrum ($m_1 \simeq m_2 \simeq m_3 \geq\sim 0.1eV$)

Since the contribution of m_3 is strongly restricted by CHOOZ, the main contributions come from m_1 and m_2, depending on their admixture

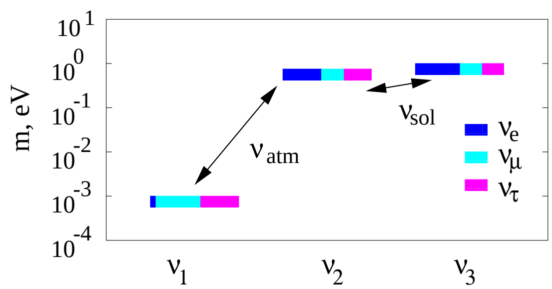

Figure 3. Neutrino masses and mixings in the inverse hierarchy scenario.

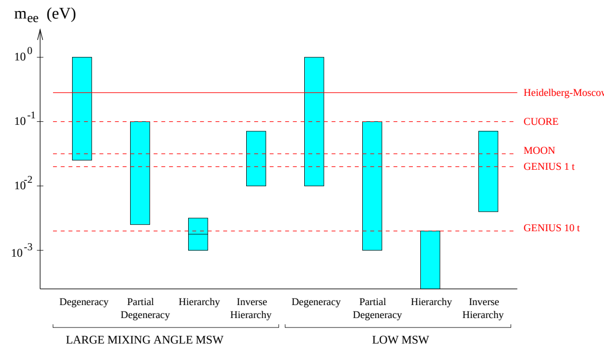

Figure 4. Summary of values for $m_{ee} \equiv \langle m \rangle$ expected from neutrino oscillation experiments (status NEUTRINO2000), in the different schemes discussed in this paper. For a more general analysis see [1]. The expectations are compared with the recent neutrino mass limits obtained from the HEIDELBERG-MOSCOW [7,17], experiment as well as the expected sensitivities for the CUORE [8] , MOON [9], EXO [10] proposals and the 1 ton and 10 ton proposal of GENIUS [11,12].

to the electron flavors, which is determined by the solar neutrino solution. We find [2]

$$m_{min} < \langle m \rangle < m_1 \quad with \tag{7}$$

$$\langle m \rangle_{min} = (\cos^2\theta_\odot - \sin^2\theta_\odot)\; m_1.$$

This leads for the LMA solution to $\langle m \rangle = (0.25 - 1) \cdot m_1$, the allowed range corresponding to possible values of the unknown Majorana CP-phases.

After these examples we give a summary of our analysis [1,2] of the $\langle m \rangle$ allowed by ν oscillation experiments for the neutrino mass models in the presently favored scenarios, in Fig. 4. The size of the bars corresponds to the uncertainty in mixing angles and the unknown Majorana CP-phases.

3. Status and Future of $\beta\beta$ Experiments

The status of present double beta experiments is shown in Fig. 1 of [19] and extensively discussed in [3]. The HEIDELBERG-MOSCOW experiment using the largest source strength of 11 kg of enriched ^{76}Ge in form of five HP Ge-detectors in the Gran-Sasso underground laboratory [3], yields after a time of 37.2 kg y of measurement (Fig. 5) a half-life limit of [17]

$$T_{1/2}^{0\nu} > 2.1(3.5) \cdot 10^{25}\; y, \quad 90\%(68\%)c.l.$$

and a limit for the effective neutrino mass of

$$\langle m \rangle < 0.34(0.26)\; eV, \quad 90\%(68\%)c.l..$$

This sensitivity just starts to probe some (degenerate) neutrino mass models. In degenerate models from the experimental limit on $\langle m \rangle$ we can conclude on upper bound on the mass scale of the heaviest neutrino. For the LMA solar solution we obtain from eq. (7) $m_{1,2,3} < 1.1 eV$ implying $\sum m_i < 3.2 eV$. This first number is sharper than what has recently been deduced from single beta decay of tritium ($m <$ 2.2 eV [25]), and the second is sharper than the limit of $\sum m_i < 5.5$. eV still compatible with most recent fits of Cosmic Microwave Background Radiation and Large Scale Structure data (see, e.g. [26]). The result has found a large resonance, and it has been shown that it excludes for example the small angle MSW solution of the solar neutrino problem in degenerate scenarios, if neutrinos are considered as hot dark matter in the universe [21–24]. Fig. 6 shows that the present sensitivity probes cosmological models including hot dark matter already now on a level of future satellite experiments MAP and PLANCK. The HEIDELBERG-MOSCOW experiment yields the by far sharpest limits worldwide. If future searches will show that

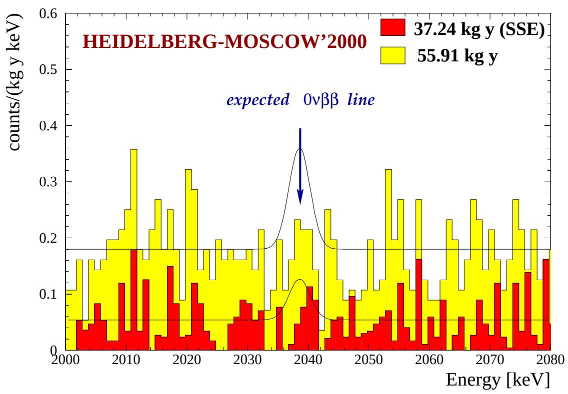

Figure 5. HEIDELBERG-MOSCOW experiment: energy spectrum in the range between 2000 keV and 2080 keV, where the peak from neutrinoless double beta decay is expected. The open histogram denoteds the overal sum spectrum without PSA after 55.9 kg y of measurement (since 1992). The filled histogram corresponds to the SSe data after 37.2 kg y. Shown are also the excluded (90%) peak areas from the two spectra.

$\langle m \rangle > 0.1$ eV, than the three-ν mass schemes, which will survive, are those with ν mass degeneracy or 4-neutrino schemes with inverse mass hierarchy (Fig. 4 and [1]). It has been discussed in detail earlier (see e.g. [11,13,19] [3]), that of present generation experiments no one (including NEMO-III, ...) has a potential to probe $\langle m_\nu \rangle$ below the present HEIDELBERG-MOSCOW level.

A possibility to probe $\langle m \rangle$ down to ~ 0.1 eV (90% c.l.) exists with the GENIUS Test Facility [18] which should reduce the background by a factor of 30 compared to the HEIDELBERG-MOSCOW experiment, and thus could reach a half-life limit of $1.5 \cdot 10^{26}$ y.

To extend the sensitivity of $\beta\beta$ experiments below this limit requires completely new experimental approaches, as discussed extensively in [11–13], and in another contribution to this conference [19].

Fig. 4 shows that an improvement of the sensitivity down to $\langle m \rangle \sim 10^{-3}$ eV is required to probe all neutrino mass scenarios allowed by present neutrino oscillation experiments. With this result of ν oscillation experiments nature seems to be generous to us since such a sensitivity seems to be achievable in future $\beta\beta$ experiment, if this method is exploited to its ultimate limit (see [19]).

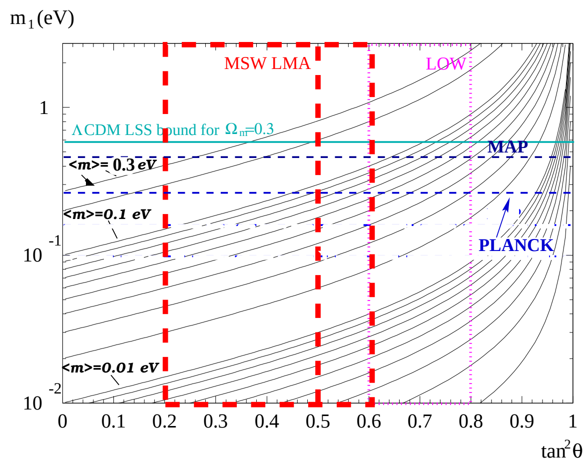

Figure 6. Double beta decay observable $\langle m \rangle$ and oscillations parameters: The case for degenerate neutrinos. Plotted on the axes are the overall scale of neutrino masses m_0 and the mixing $\tan^2 2\theta_{12}$. Also shown is a cosmological bound deduced from a fit of CMB and large scale structure [14] and the expected sensitivity of the satellite experiments MAP and Planck. The present limit from tritium β decay of 2.2 eV [27] would lie near the top of the figure. The range of $\langle m \rangle$ investigated at present by the HEIDELBERG-MOSCOW experiment is, in the case of small solar neutrino mixing already in the range to be explored by MAP and Planck [14].

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Elsevier instructions for the preparation of a 2-column format camera-ready paper in LaTeX

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Text should be produced within the dimensions shown on these pages: each column 7.5 cm wide with 1 cm middle margin, total width of 16 cm and a maximum length of 20.2 cm on first pages and 21 cm on second and following pages. The LaTeX document class uses the maximal stipulated length apart from the following two exceptions (i) LaTeX does not begin a new section directly at the bottom of a page, but transfers the heading to the top of the next page; (ii) LaTeX never (well, hardly ever) exceeds the length of the text area in order to complete a section of text or a paragraph. Here are some references: [1,2].

1.1. Spacing

We normally recommend the use of 1.0 (single) line spacing. However, when typing complicated mathematical text LaTeX automatically increases the space between text lines in order to prevent sub- and superscript fonts overlapping one another and making your printed matter illegible.

1.2. Fonts

These instructions have been produced using a 10 point Computer Modern Roman. Other recommended fonts are 10 point Times Roman, New Century Schoolbook, Bookman Light and Palatino.

*Footnotes should appear on the first page only to indicate your present address (if different from your normal address), research grant, sponsoring agency, etc. These are obtained with the `\thanks` command.

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The printout submitted should be an original; a photocopy is not acceptable. Please make use of good quality plain white A4 (or US Letter) paper size. *The dimensions shown here should be strictly adhered to: do not make changes to these dimensions, which are determined by the document class.* The document class leaves at least 3 cm at the top of the page before the head, which contains the page number.

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3. TABLES AND ILLUSTRATIONS

Tables should be made with LaTeX; illustrations should be originals or sharp prints. They should be arranged throughout the text and preferably be included *on the same page as they are first discussed*. They should have a self-contained caption and be positioned in flush-left alignment with the text margin within the column. If they do not fit into one column they may be placed across both columns (using `\begin{table*}` or `\begin{figure*}` so that they appear at the top of a page).

3.1. Tables

Tables should be presented in the form shown in Table 1. Their layout should be consistent throughout.

Horizontal lines should be placed above and below table headings, above the subheadings and at the end of the table above any notes. Vertical lines should be avoided.

If a table is too long to fit onto one page, the table number and headings should be repeated above the continuation of the table. For this you have to reset the table counter with `\addtocounter{table}{-1}`. Alternatively, the table can be turned by 90° ('landscape mode') and spread over two consecutive pages (first an even-numbered, then an odd-numbered one) created by means of `\begin{table}[h]` without a caption. To do this, you prepare the table as a separate LaTeX document and attach the tables to the empty pages with a few spots of suitable glue.

3.2. Useful table packages

Modern LaTeX comes with several packages for tables that provide additional functionality. Below we mention a few. See the documentation of the individual packages for more details. The packages can be found in LaTeX's `tools` directory.

`array` Various extensions to LaTeX's `array` and `tabular` environments.

`longtable` Automatically break tables over several pages. Put the table in the `longtable` environment instead of the `table` environment.

Table 2: The next-to-leading order (NLO) results *without* the pion field.

Λ (MeV)	140	150	175	200	225	250	Exp.	v_{18} [?]
r_d (fm)	1.973	1.972	1.974	1.978	1.983	1.987	1.966(7)	1.967
Q_d (fm^2)	0.259	0.268	0.287	0.302	0.312	0.319	0.286	0.270
P_D (%)	2.32	2.83	4.34	6.14	8.09	9.90	–	5.76
μ_d	0.867	0.864	0.855	0.845	0.834	0.823	0.8574	0.847
$\mathcal{M}_{\mathrm{M1}}$ (fm)	3.995	3.989	3.973	3.955	3.936	3.918	–	3.979
$\mathcal{M}_{\mathrm{GT}}$ (fm)	4.887	4.881	4.864	4.846	4.827	4.810	–	4.859
$\delta_{1\mathrm{B}}^{\mathrm{VP}}$ (%)	−0.45	−0.45	−0.45	−0.45	−0.45	−0.44	–	−0.45
$\delta_{1\mathrm{B}}^{\mathrm{C2:C}}$ (%)	0.03	0.03	0.03	0.03	0.03	0.03	–	0.03
$\delta_{1\mathrm{B}}^{\mathrm{C2:N}}$ (%)	−0.19	−0.19	−0.18	−0.15	−0.12	−0.10	–	−0.21

The experimental values are given in ref. [4].

Table 1
The next-to-leading order (NLO) results *without* the pion field.

Λ (MeV)	140	150	175	200
r_d (fm)	1.973	1.972	1.974	1.978
Q_d (fm^2)	0.259	0.268	0.287	0.302
P_D (%)	2.32	2.83	4.34	6.14
μ_d	0.867	0.864	0.855	0.845
$\mathcal{M}_{\rm M1}$ (fm)	3.995	3.989	3.973	3.955
$\mathcal{M}_{\rm GT}$ (fm)	4.887	4.881	4.864	4.846
$\delta_{\rm 1B}^{\rm VP}$ (%)	-0.45	-0.45	-0.45	-0.45
$\delta_{\rm 1B}^{\rm C2:C}$ (%)	0.03	0.03	0.03	0.03
$\delta_{\rm 1B}^{\rm C2:N}$ (%)	-0.19	-0.19	-0.18	-0.15

The experimental values are given in ref. [4].

`dcolumn` Define your own type of column. Among others, this is one way to obtain alignment on the decimal point.

`tabularx` Smart column width calculation within a specified table width.

`rotating` Print a page with a wide table or figure in landscape orientation using the `sidewaystable` or `sidewaysfigure` environments, and many other rotating tricks. Use the package with the `figuresright` option to make all tables and figures rotate in clockwise. Use the starred form of the `sideways` environments to obtain full-width tables or figures in a two-column article.

3.3. Line drawings

Line drawings should be drawn in India ink on tracing paper with the aid of a stencil or should be glossy prints of the same; computer prepared drawings are also acceptable. They should be attached to your manuscript page, correctly aligned, using suitable glue and *not transparent tape*. When placing a figure at the top of a page, the top of the figure should be at the same level as the bottom of the first text line.

All notations and lettering should be no less than 2 mm high. The use of heavy black, bold lettering should be avoided as this will look unpleasantly dark when printed.

3.4. PostScript figures

Instead of providing separate drawings or prints of the figures you may also use PostScript files which are included into your LaTeX file and printed together with the text. Use one of the packages from LaTeX's `graphics` directory: `graphics`, `graphicx` or `epsfig`, with the `\usepackage` command, and then use the appropriate commands (`\includegraphics` or `\epsfig`) to include your PostScript file.

The simplest command is:
`\includegraphics{file}`, which inserts the PostScript file `file` at its own size. The starred version of this command:
`\includegraphics*{file}`, does the same, but clips the figure to its bounding box.

With the `graphicx` package one may specify a series of options as a key–value list, e.g.:

```
\includegraphics[width=15pc]{file}
\includegraphics[height=5pc]{file}
\includegraphics[scale=0.6]{file}
\includegraphics[angle=90,width=20pc]{file}
```

See the file `grfguide`, section “Including Graphics Files”, of the `graphics` distribution for all options and a detailed description.

The `epsfig` package mimicks the commands familiar from the package with the same name in LaTeX2.09. A PostScript file `file` is included with the command `\psfig{file=file}`.

Grey-scale and colour photographs cannot be included in this way, since reproduction from the

printed CRC article would give insufficient typographical quality. See the following subsections.

Figure 1. Good sharp prints should be used and not (distorted) photocopies.

Figure 2. Remember to keep details clear and large enough.

3.5. Black and white photographs

Photographs must always be sharp originals (*not screened versions*) and rich in contrast. They will undergo the same reduction as the text and should be pasted on your page in the same way as line drawings.

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Sharp originals (*not transparencies or slides*) should be submitted close to the size expected in publication. Charges for the processing and printing of colour will be passed on to the author(s) of the paper. As costs involved are per page, care should be taken in the selection of size and shape so that two or more illustrations may be fitted together on one page. Please contact the Technical Editor in the Camera-Ready Publications Department at Elsevier for a price quotation and layout instructions before producing your paper in its final form.

4. EQUATIONS

Equations should be flush-left with the text margin; LaTeX ensures that the equation is preceded and followed by one line of white space. LaTeX provides the package `fleqn` to get the flush-left effect.

$$H_{\alpha\beta}(\omega) = E_\alpha^{(0)}(\omega)\delta_{\alpha\beta} + \langle\alpha|W_\pi|\beta\rangle \qquad (1)$$

You need not put in equation numbers, since this is taken care of automatically. The equation numbers are always consecutive and are printed in parentheses flush with the right-hand margin of the text and level with the last line of the equation. For multi-line equations, use the `eqnarray` environment. For complex mathematics, use the $\mathcal{AMS}$-LaTeX package.

REFERENCES

1. S. Scholes, Discuss. Faraday Soc. No. 50 (1970) 222.
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4. D.L. Eaton, Porous Glass Support Material, US Patent No. 3 904 422 (1975).

References should be collected at the end of your paper. Do not begin them on a new page unless this is absolutely necessary. They should be prepared according to the sequential numeric

system making sure that all material mentioned is generally available to the reader. Use `\cite` to refer to the entries in the bibliography so that your accumulated list corresponds to the citations made in the text body.

Above we have listed some references according to the sequential numeric system [1–4].